INTRODUCTION

Unwinding and winding, on a continuous basis, requires automated splice and transfer systems. A number of web cut-off technologies are available for us to choose from, among them being shear, traversing knife, rotating knife and rupture knife. Unwind splices can be lap or butt type. Winder transfers can be with or without fold-over. The selection of the technology that is to be employed is dependent upon the needs of the overall process and the physical properties of the web materials that are to be processed.

For this discussion, we have chosen to limit our focus to the core elements found in what is commonly referred to as the “bump and cut” splice and transfer techniques, which techniques are most commonly employed for thin film applications. When preparing to design and manufacture the splicing and transfer components of a high-speed, automated turret unwind or winder, several key components and their control must be addressed. This presentation concentrates on the bump roll and cut-off knife assemblies, as well as the control equipment used to ensure both their speed and repeatability.

BUMP ROLL

Since the bump roll is one of the major components when splicing or doing a core transfer, one can optimize its design by considering the following factors:

1. Roll Weight:
Roll weight is dependent on the roll design and materials of construction. In high-speed applications, one looks to minimize the weight to reduce the inertia, while maximizing the material strength necessary to sustain the impact the roll undergoes during the splice or transfer process. Most bump rolls are constructed of aluminum or carbon fiber composite material, fitted with extremely free-turning internal bearings and mounted on a non-rotating center support shaft. This design allows the support shaft to be (tendency) driven, using the bearing friction to increase the roll speed to approximately match that of the web before it makes contact. One must always remember to include the weight of any elastomer covering when determining the roll weight, since this can be a significant factor.
2. **Roll Deflection:**
The deflection of a roll is important to its behavior, especially at high speeds. The geometry of the web path when it contacts the roll must be considered. In instances when the roll weight and web tension act in the same direction, the deflection will be maximized. If the web passes under the roll, web tension will oppose roll weight, reducing the deflection. Determine the situation that gives the worst deflection.

3. **Investigate Critical Roll Speed:**
Any object made of an elastic material has a natural period of vibration. At the speed at which the centrifugal force due to rotation exceeds the elastic resisting force (critical speed), the object will vibrate and fail unless it is restrained. Even before any failure occurs, the vibration will cause both the machine and the web being processed to be out of control. First calculate the speed (rpm) of the bump roll when operating at maximum line speed. In addition, calculate the speed of the roll at any point where the deflection is high, since that may define the critical roll speed. To determine the critical roll speed at a particular deflection, one can use the formula:

\[
N_c = \frac{187.7}{\sqrt{Y}}
\]

\(N_c = \text{critical speed (rpm)}\)
\(Y = \text{deflection (inches)}\)

For example, a 6 inch diameter bump roll that deflects 0.010 inch, has a critical speed that occurs at 1877 rpm, which is equivalent to 2948 fpm. Good design practice suggests operating this roll at no more than 80% of the critical speed calculated, or 2360 fpm. This allows a reasonable margin for error.

4. **Roll Inertia:**
In addition to the mechanical deflection calculated in (3) above, one must determine the rotational (polar moment of inertia) inertia of the bump roll. While any elastomer covering is not included in the mechanical deflection calculation, its weight and dimensions are important when determining the rotational inertia. To determine the roll inertia, one can use the formula:

\[
J = 0.5 \frac{W (R_o^2 + R_i^2)}{144}
\]

\(J = \text{Polar Moment of Inertia (lb-ft}^2\)
\(W = \text{Roll component weight (lbs)}\)
\(R_o = \text{Outer Radius (inches)}\)
\(R_i = \text{Inner Radius (inches)}\)

Once the above formula is applied to both the roll body and the elastomer covering, the total roll inertia, which is the arithmetic sum of those components, can be determined. Table 1 shows the inertia values for various roll designs and materials of construction, both with and without any covering. One can see that the elastomer covering is a major contributor to the total inertia.
Table 1: Roll Inertia Values

<table>
<thead>
<tr>
<th>Roll (66” Face)</th>
<th>Weight (lbs.)</th>
<th>Inertia Values (lb-ft(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without</td>
<td>with</td>
</tr>
<tr>
<td></td>
<td>cover</td>
<td>cover</td>
</tr>
<tr>
<td>6” O.D. x 5” I.D. Dead Shaft Aluminum</td>
<td>57</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.014</td>
</tr>
<tr>
<td>6” O.D. x 5.5” I.D. Dead Shaft Aluminum</td>
<td>30</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.714</td>
</tr>
<tr>
<td>6” O.D. x 5.75” I.D. Composite Material</td>
<td>16</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.913</td>
</tr>
<tr>
<td>6” O.D. x 5” I.D. Live Shaft Aluminum</td>
<td>64</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.313</td>
</tr>
</tbody>
</table>

5. **Roll Covering:**
Bump rolls are normally covered with a compliant elastomer (rubber) material that provides resiliency, durability and surface firmness to assist in the splice or transfer process. In an effort to reduce the effective weight of the covering by reducing its thickness, one must ensure that the covering has the resilience to meet the impact requirements. Reducing the hardness (durometer) to improve resiliency for the thinner covering may result in low splice pressure. Typically, a 6 inch core diameter bump roll may be covered with a 1/2 inch thick, 45 – 55 durometer, Shore A hardness rubber. In certain instances, proprietary double durometer coverings have been used to provide splice or transfer features that conventional coverings cannot duplicate, particularly as it pertains to roll bounce. These coverings offer a firm surface with a shock absorbing, softer inner core.

6. **Roll Support Components:**
While the previous sections refer specifically to the bump roll, one must also consider minimizing the inertia of the roll support assembly to complete the design. This is of paramount importance when accelerating the roll assembly for splicing or transfer functions. The use of 2000 Series aluminum material to manufacture the roll pivot plates, actuating brackets and pneumatic cylinder supports offers the strength of steel at the much lower weight of aluminum. Smaller actuator components lead to a compact, lightweight design.

**CUT-OFF KNIFE**

While there are a number of methods that can be used to cut a web, this paper will concentrate on the rupture type cut-off knife. The knife assembly is subjected to multiple forces that bend and twist it, particularly as the web is impaled on the teeth and later cut. These forces include those to accelerate the knife assembly prior to web impact, impact forces generated when the knife first impales the moving web, and the force required to cut the web. The acceleration force is a function of the mass and geometry of the moving assembly and can be readily calculated. The impact and cutting forces vary, however, dependent upon the different tooth geometries, as well as the physical characteristics of the material being cut. While calculations may be attempted, numerous assumptions will be required, suggesting that actual cutting trials should be conducted to select the knife that operates best with a specific web.
Shown below are some knife tooth profiles, each of which are used for cutting different materials. *Photo 1* shows a dual angle, deep tooth knife. Notice how the teeth are pitched from the center out to each edge, providing a spreading action during the cut-off process. The force on the knife is uniformly distributed across the aligned teeth. In comparison, *Photo 2* shows a knife with two sets of teeth, the longer of which penetrate the web at impact, followed by the shorter teeth completing the cut. This knife is better suited for cutting tougher materials, since the force at impact is distributed on fewer teeth. *Photos 3 and 4* are representative of other knives, whose tooth height and pitch can be varied as required to satisfy a particular cut-off requirement.

To determine the reaction of the knife and holder assembly to the maximum force that occurs during a web cut, one must know the following information:

1. The physical and mechanical properties of the knife and holder assembly, including materials of construction, size, weight and moment of inertia along both rectangular coordinates.
2. The physical and mechanical properties of the web, including its thickness, width and tensile strength.
3. The position of the assembly with respect to the web at the point where the knife impales it.
4. The maximum speed of the process line.
Referring to Figure 1 at the left, consider an unwind cut-off knife assembly positioned to sever a web which contacts the knife at Angle \( \theta \). Based on the physical properties of the web and its speed, it is determined that a force \( F \) will be developed at the knife during the process. Since the force is applied at an angle to the knife, it will result in both bending and twisting. The force must be resolved along both coordinate axes (\( F \sin \theta \) and \( F \cos \theta \)), so the respective deflections and the maximum material stress can be calculated. This ensures that the design criteria for the materials used to construct the assembly are met.

While this satisfies the mechanical design, it does not address the equally important issue of what occurs when the knife “whips” due to its acceleration and impact with the moving web. Since the knife assembly is restrained at both ends and subjected to this transverse force, it should be designed to maximize stiffness while using high strength-to-weight materials to reduce inertia. By performing cutting trials, the knife “whip” can be studied using a high-speed camera (see Photos 5&6 below). This will confirm the movement of the knife during acceleration, at impact and recoil, as well as the time it takes for the vibration upset to dampen. If the displacement is too great, the knife may contact the roll of material being processed, resulting in a splice or transfer failure.

Photo 5
Web impact bends knife; note gap in holder

Photo 6
Knife recoils after cut; holder gap restored
CONTROL EQUIPMENT

Intertwined with the mechanical design of the bump and cut systems’ components are the controls required to allow for successful, repeatable unwind and winder splices and transfers. The selection of the appropriate components is critical in the overall system design.

Of paramount importance is the ability to control the mechanical components with a high degree of repeatability. In order to do this, it is necessary to identify those components that play a major role in the control scheme. Once these components are identified and analyzed, the system can be designed to minimize their effect.

The controls that most closely affect the process are the pneumatic valves and high speed counter modules. When selecting the pneumatic valve, spool shifting consistency is as equally important as valve speed. Published data and experimentation show that a time lag occurs during the interval when a pneumatic control valve is energized and the valve shifts. Selecting a valve where that variation is consistent is important. When using a high speed counter module, selecting a unit that has an output triggering time of approximately 20 to 50 micro-seconds greatly reduces the time it takes for the system to react to inputs and outputs.

In high speed operations, the bump roll and knife firing sequences must be engineered to compensate for time lags such as those outlined above. However, this is only as accurate as the repeatability of the devices selected, since the engineered solution can only account for that portion of the lag which is constant. The time lag for a particular device can be broken down as follows:

\[ TL = TLc + TLv \]

- \( TL = \text{Total Device Time Lag} \)
- \( TLc = \text{Device’s Constant Time Lag} \)
- \( TLv = \text{Device’s Variable Time Lag} \)

As stated previously, there are several items that affect the total time lag (TL). In this case, compensation can be made for the constant time lag (TLc). Therefore, the repeatability of the system’s design becomes a function of the sum of the variable time lags (TLv) of the components.

As an example, consider a web running at 2400 fpm. This equates to a web speed of 0.48 inches/millisecond. Assume that a pneumatic valve, which can be consistently energized and shifted in 29 – 32 milliseconds, is being used to fire a device (bump roll or knife). In addition, consider using a high speed counter module with a 50 micro-second output triggering time. When one combines the use of the two devices, the total time lag (TL) is 29 - 32 milliseconds. This time lag results in 13.92 – 15.36 inches of web passing a given point. However, since the system can be designed to compensate for the constant time lag (TLc) of the valve, namely 29 milliseconds, it results in a total system variable time lag (TLv) of 0 – 4 milliseconds, during which time 0 – 1.92 inches of web passes.
As the above indicates, it is important to select components and devices that maximize repeatability. By doing so, the control system can be designed to minimize waste while maximizing system repeatability.

**SUMMARY**

When unwind splicing or doing winder transfers of thin films at high speeds, strong emphasis must be placed on the engineering, design and manufacture of the bump roll, cut-off knife assembly and their control systems. Failure to minimize the inertia of the bump roll, while maintaining sufficient stiffness and a resilient elastomer covering, is the major cause of missed splices or transfers. Similarly, the critical speed of the roll is a more important factor when operating at higher line speeds. The cut-off assembly must be designed to withstand the greater impact forces encountered when processing at higher speeds. The design must satisfy the requirements of lightweight construction, stiffness and low inertia, to allow repeatability during splice or transfer processes. Finally, the pneumatic and electrical controls selected must be consistent in their high-speed response, thereby optimizing repeatability that ensures proper control of the process.
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